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An outburst of the magnetic cataclysmic variable XY Arietis observed with *RXTE*

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ABSTRACT
We report the first observed outburst of the magnetic cataclysmic variable XY Ari. X-ray observations show a flux increase by an order of magnitude the day after the first signs of outburst. During the 5-d duration the X-ray spin pulse is greatly enhanced and the X-ray spectrum far more absorbed. We suggest that the inner disc pushes inwards during outburst, blocking the view to the lower accreting pole, breaking the symmetry present in quiescence, and so producing a large pulsation. The observations are consistent with a disc instability as the cause of the outburst, although we can't rule out alternatives. We draw parallels between our data and the UV delay and dwarf nova oscillations seen in non-magnetic dwarf novae.

Key words: accretion, accretion discs – novae, cataclysmic variables – binaries: close – binaries: eclipsing – stars: individual: XY Ari – X-rays: stars.

1 INTRODUCTION

The dwarf nova (DN) eruption is one of the most distinctive features of the cataclysmic variables (CVs). Such stars brighten by typically 3–5 magnitudes for durations of 4–8 d every 20–60 d. There are also longer, brighter 'superoutbursts' and other related phenomena (for a comprehensive review see Warner 1995a). The near unanimous opinion is that the outbursts are caused by instabilities in the accretion disc surrounding the white dwarf in these close binaries. Because of the hydrogen ionization instability a disc with the right conditions can choose either of two states (one hot and viscous, the other cooler and more fluid) for a given surface density. The disc cycles between the states, dumping material onto the white dwarf at a higher rate when it is hot and viscous (reviewed by Osaki 1996). The alternative proposal, that instabilites in the secondary star increase the mass transfered into the disc, is decreasingly favoured for typical DN eruptions, but might still have a role to play in explaining the full phenomenology of CVs.

While outbursts in non-magnetic DNe are well studied, far fewer have been seen in magnetic systems. In AM Her stars, which don't have discs, the lack of outbursts is expected. The intermediate polars (IPs), which have weaker fields and are not phase-locked, but do possess at least partial discs, show several variations on the DN theme. These are reviewed below to set the scene for this paper.

XY Ari is an IP lying behind a molecular cloud (Patterson & Halpern 1990) and so cannot be seen in the optical. X-ray and infra-red studies (Kamata, Tawara & Koyama 1991; Zuckerman et al. 1993; Allan, Hellier & Ramseyer 1996) show it have a 6.06-h orbital period and a 206-s spin period, and reveal deep eclipses implying an inclination of $>80°$. To use the X-ray eclipse to study the accretion regions we observed 20 eclipses of XY Ari with *RXTE* (Bradt, Rothschild & Swank 1993). The results are reported in Hellier (1997a). However, XY Ari went into outburst during the observations, the first ever seen of this star. It is also only the second magnetic CV to have been observed in outburst in X-rays, after GK Per (Watson, King & Osborne 1985). This paper reports the outburst and discusses its implications for IPs and other CVs.

1.1 Outbursts in intermediate polars

Table 1 lists the six well-established IPs which have shown outbursts, together with the relevant literature (see Hellier 1993a and Warner 1997 for previous compilations). GK Per has a long orbit and an evolved secondary, and its month-long outbursts can be explained as disc instabilities when the parameters are adjusted for GK Per's peculiarities (Kim, Wheeler & Mineshige 1992). YY Dra, and now XY Ari, have shown outbursts lasting 5 days, which is typical of DNe. The recurrence time for YY Dra's outbursts (several years) is an order of magnitude greater than typical. However, the inner disc is missing in an IP, and, since the disc thus needs to dissipate less angular momentum, its outer radius can be less than in non-magnetic systems. The truncated disc takes longer to accumulate sufficient material for an outburst (Angelini & Verbunt 1989; Warner 1997). The latter paper pre-

Table 1. Intermediate Polars showing outbursts

Star	Length (day)	Δmag	Interval	P_{orb} (hr)	P_{spin} (secs)
V1223 Sgr	0.5	>1	?	3.37	745
TV Col	0.5	2	∼ 1 month?	5.49	1910
EX Hya	2	4	∼ yrs, erratic	1.64	4022
XY Ari	5	∼ 3	≳ 50 d	6.06	206
YY Dra	5	5	∼ 1000 d	3.96	529
GK Per	50	3	880–1240 d	47.9	351

Refs: V1223 Sgr: van Amerongen & van Paradijs 1989. TV Col: Szkody & Mateo 1984; Schwarz et al. 1988; Hellier & Buckley 1993. EX Hya: Bateson et al. 1970; Hellier et al. 1989; Reinsch & Beuermann 1990; Buckley & Schwarzenberg-Czerny 1993. XY Ari: This paper. YY Dra: Patterson et al. 1992; Mattei 1996b. GK Per: Watson et al. 1985; Bianchini et al. 1986; Kim et al. 1992; Mattei 1996a; Morales-Rueda et al. 1996.

dicted that XY Ari should have outbursts similar to those of YY Dra, which this paper shows to be correct.

Note that the three stars mentioned so far have spin periods less than 5 per cent of the orbital periods, atypically low amongst IPs. This means that their magnetospheres are small in comparison with the discs, allowing the discs to behave similarly to those in non-magnetic systems.

The remaining three stars showing outbursts, EX Hya, TV Col and V1223 Sgr, are among the majority of IPs with spin periods greater than 5 per cent of the orbital period, where much more of the inner disc is magnetically disrupted. These stars present more of a problem for the disc instability model. While their low amplitudes, short durations, and long recurrence times can to some extent be explained by disc trunction (Angelini & Verbunt 1989), the small fraction of the transfered material involved in the outbursts is atypical, and suggests that disc instabilities are suppressed, with the observed outbursts having a different cause (Warner 1997).

Hellier et al. (1989) and Hellier & Buckley (1993) proposed that the outbursts in these three stars result from increased mass transfer from the secondary. The evidence for this (or at least against the disc-instability model) can be summarised as: (1) In all three stars the line emission increases during outburst, in contrast to normal DN behavior. (2) In both EX Hya and TV Col the line emission from the bright-spot where the stream hits the disc increases relative to the rest of the system during outburst, suggesting increased mass transfer from the secondary. (3) EX Hya shows the stream oveflowing the disc in outburst, but not in quiescence, a possible consequence of an enhanced stream. (4) The optical eclipse in EX Hya is centered later in outburst than quiescence (Reinsch & Beuermann 1990) also suggesting an enhanced stream. (5) The eccentric disc in TV Col shows a phase glitch in outburst, as expected if it encounters a large amount of new material. (6) V1223 Sgr shows VY Scl low states (Garnavich & Szkody 1988) in addition to outbursts. Since VY Scl stars in their high state are on the hot side of the disc instability, according to the usual picture, the outbursts seen on top of the high states can't be disc instabilities. (7) EX Hya has shown two outbursts separated by 8 days, and also periods of >3 y without outbursts, but no difference in the quiescent magnitude. This is hard to account for in the disc instability model.

In addition, there is substantial evidence that similar short, low-amplitude outbursts occur in other types of CV, often hidden amongst the disc instabilities. Bateson (1991) lists many such flares in non-magnetic DNe; a particularly well studied example is presented by Echevarria et al. (1996), who interpret it as a mass transfer event. Further, O'Donoghue (1990) saw one anomalous eclipse profile of Z Cha early in a superoutburst, which implied a bright spot 20 times more luminous than in quiesence. There has also been a short-lived flare from the AM Her star QS Tel observed in the EUV (Warren et al. 1993). Since AM Her stars don't have discs this can only have been a mass-transfer event or a secondary star flare. AM Her stars also have low states (e.g. Cropper 1990), which must be caused by mass-transfer variations, although the timescales (typically months) are longer than the flares and outbursts discussed here.

2 OBSERVATIONS

The 20 eclipse egresses were observed by *RXTE* over the period 1996 July 13 to 1996 August 11, at a rate of roughly one per day. Each observation lasted ∼ 2000 s, with the first 1000 s in eclipse and the later half covering ∼ 5 spin cycles. For this paper we discard the eclipse and egress information (for which see Hellier 1997a) and concentrate on the outburst.

We extracted lightcurves in the energy range 2–15 keV, using data from the top Xenon layer of the PCA only [this gives a higher signal-to-noise (S/N) for dim sources]. We then subtracted the background estimated using PCABACKEST v1.4f. This marginally underestimated the count rate in eclipse, so, as a final step, we fitted a straight line to the data in eclipse, extrapolated it through the observation, and subtracted it to give zero counts in eclipse.

The 20 lightcurves are presented in Fig. 1. Note that in reality the gaps between the observations (∼ 1 d) are large compared to the length of each observation (∼ 15 min), but they are highly contracted to display the whole dataset in one plot.

3 THE SPIN PULSE

The most striking aspect of Fig. 1 is that while the mean count rate increases during the outburst, the amplitude of the spin pulse increases from a quiescent level of 20–30 per cent (so low that it is hard to see amongst the flickering) to 80–90 per cent. Furthermore the increase in pulse amplitude occurs a day before the average count rate rises. This is illustrated in Fig. 2, which shows the mean count rate and pulse amplitude, plotted, this time, on a continuous time axis.

Fig. 3 compares the pulse profiles at all stages through the outburst. The quiescent pulse (the average of all 14 observations before and after the outburst) is shown at the bottom and top of the plot. It has a low amplitude and is

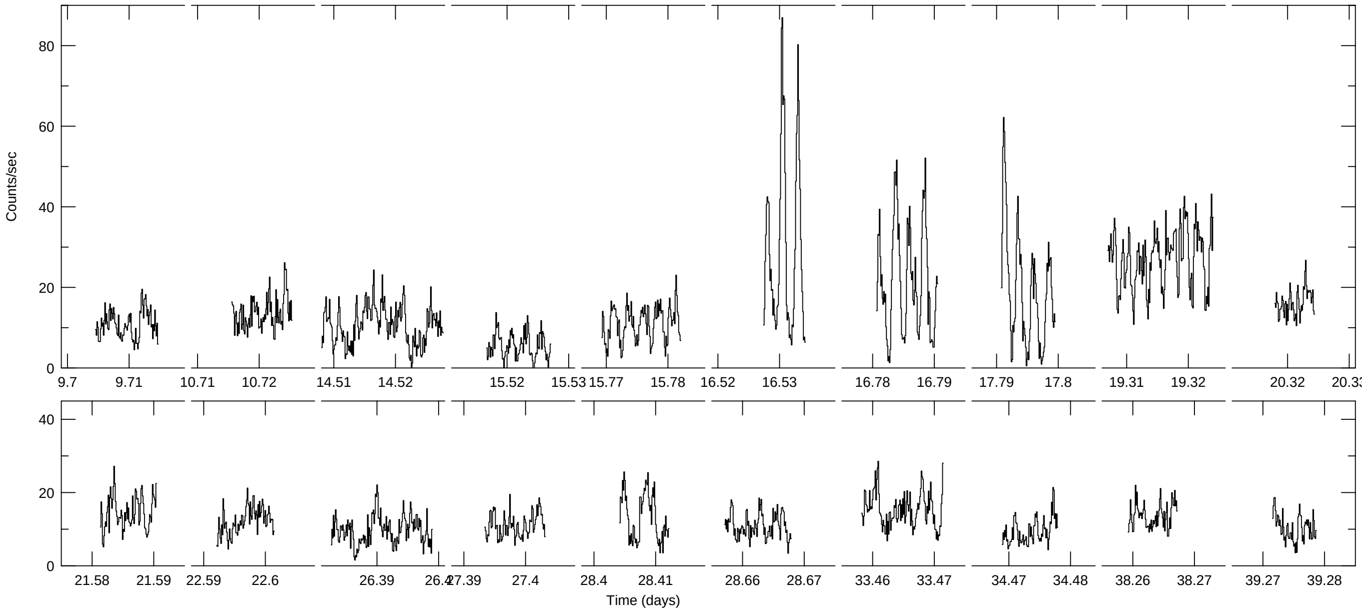

Figure 1. The 20 *RXTE* lightcurves of XY Ari. Day zero (here and in Fig. 2) is HJD 245 0267.8525 or 1996 July 3, 8:32 UT.

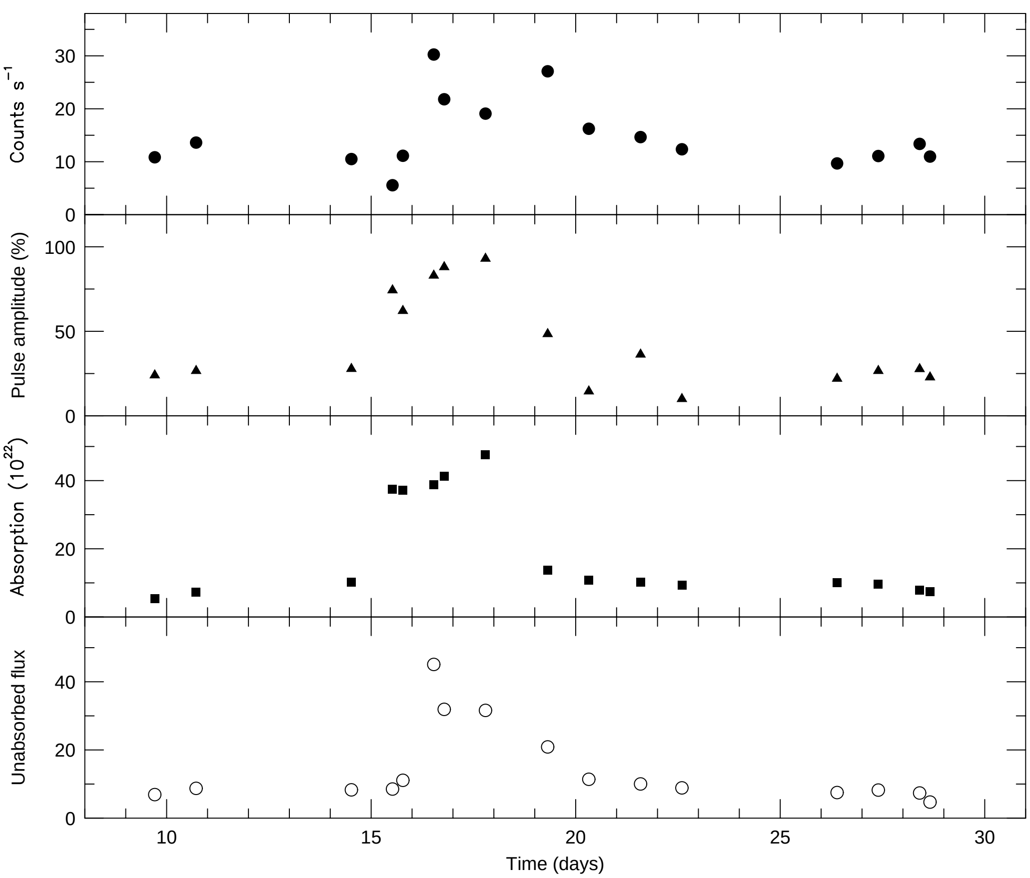

Figure 2. The top panel shows the average count rate in each of the 20 observations. The next panel show the amplitude of the pulsation in each observation, obtained by fitting the folded data with a sinusoid and recording the full amplitude of the sinusoid divided by the peak value. The third and bottom panels show the results of fitting the spectrum from each observation with a simple model of a 30 keV bremsstrahlung plus absorption. The absorption column (third panel) is in units of 10^{22} cm^{-2}, while the bottom panel shows the relative normalisation of the bremsstrahlung emission. Formal photon-noise error bars are comparable to the size of the plotted symbols. However, in all cases uncertainty due to flickering or model ambiguity is greater than errors derived from photon statistics.

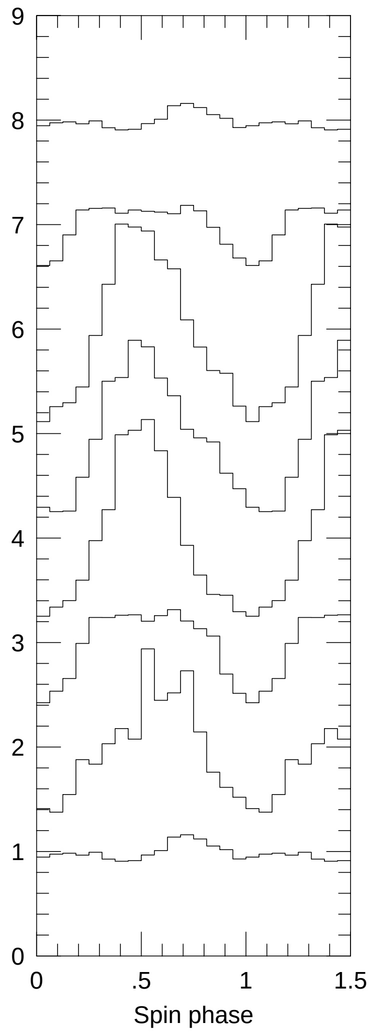

Figure 3. The evolution of the spin pulse through the outburst. The folded data from all 14 quiescent observations are shown both at the top and the bottom. The pulse profiles from the outburst observations are shown with time increasing upwards. Each pulse has been normalized to have a mean value of 1 and an offset of 1 is added to each successive profile for clarity. Thus the zero point is at zero for the first profile, and increases by 1 each time. Again, photon-noise errors are small (see Fig. 4), and the dominant source of uncertainty is flickering.

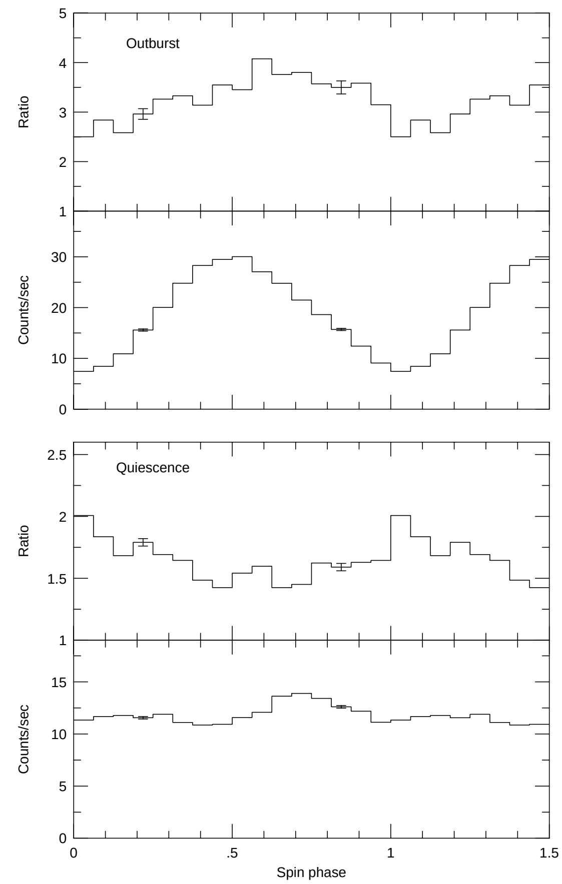

Figure 4. The upper two panels show the average spin pulse from all 6 outburst observations, together with the 6–15/2–5 keV hardness ratio. The lower panels are the same for the 14 quiescent observations. The spin phase is defined so that the upper magnetic pole is in the middle of the white dwarf face at phase 0.5 (see text).

double-peaked (as it was in the *Ginga* observations reported by Kamata & Koyama 1993). The 6 outburst observations (observations 4 to 9 in Fig. 2) follow in order from the bottom upwards. In outburst the profile becomes single peaked, and at the peak of the outburst it is nearly sinusoidal. However, both on the rise and fall (observations 5 and 9) the profile is flat topped.

The mean quiescent and outburst pulse profiles are shown together with the 6–15/2–5 keV hardness ratios in Fig. 4. The hardness ratio increases markedly in the outburst, from ~ 1.7 to ~ 3. Further, during outburst, the hardness ratio varies with spin phase, being greater at flux maximum.

4 THE SPECTRUM

The quiescent spectrum is adequately fit by an absorbed 30 keV bremsstrahlung, although the adequacy derives largely from the limited spectral resolution of *RXTE* and the low number of counts from such short observations. As a check we extracted from the archive the 40 ks *ASCA* observation of XY Ari performed on 1995 August 7. The spectral resolution of *ASCA* is much better but the low count rate of 0.158 counts s^{-1} limits the usefulness of the data. The 0.5–10 keV SIS and GIS spectra are again well fitted by a bremsstrahlung with a (fixed) temperature of 30 keV and an absorption column of 6×10^{22} H atom cm^{-2}. With the addition of an iron line at 6.6 keV, this model gives χ^2_ν = 1.0.

The spectra during outburst show greatly increased absorption, explaining the increased hardness ratio (Fig. 5). To investigate this we fitted the spectra from all 20 observations with the same absorbed 30 keV bremsstrahlung model, allowing the column and the normalisation of the bremsstrahlung to optimise for each observation individually. The resulting parameters are plotted in the lower panels of Fig. 2. While this model fits the quiescent data adequately

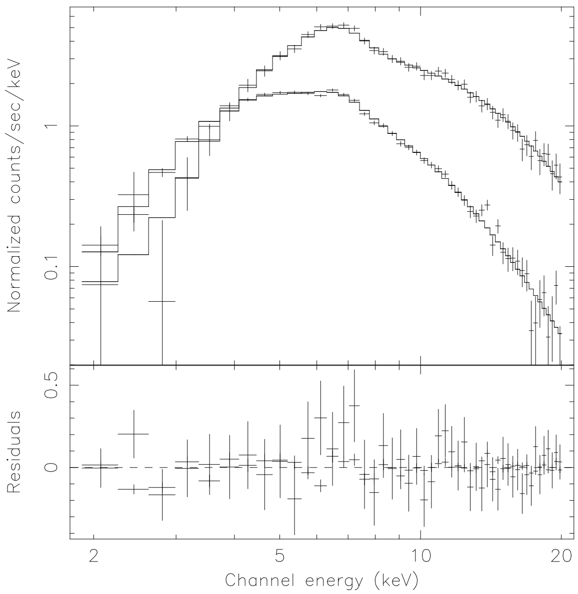

Figure 5. The spectrum from the peak of the outburst (observation 6) compared with the averaged quiescent spectrum. The quiescent spectrum is fitted with an absorbed bremsstrahlung plus an iron line, while the outburst model contains an additional partial absorber (see Section 4). The observed fluxes are 3.1×10^{-11} (quiescence) and 11.5×10^{-11} (outburst) erg cm^{-2} s^{-1} over 2.0–20.0 keV. The corresponding unabsorbed fluxes are 4.2×10^{-11} and 66.0×10^{-11} erg cm^{-2} s^{-1} respectively.

($\chi^2_\nu = 1.0$), it was a poorer fit to the outburst spectra ($\chi^2_\nu = 1.8$).

Unfortunately, the low spectral resolution of *RXTE* means that fitting more complex models to the outburst spectra becomes ambiguous. They can be fit by any of (1) adding a further, dense, partial-covering absorber; (2) adding lower temperature bremsstrahlung or black-body components; or (3) adding a broad iron line together with a deep iron edge.

We prefer the first model because it is consistent with the increased absorption required whatever the model; because it gives the lowest χ^2_ν overall; and because there is little sign of the other features in the quiescent *RXTE* or *ASCA* spectra. Further, the dense partial absorber is consistent with our interpretation of the spin pulse (see Section 5). This model gives $\chi^2_\nu = 0.95$ in a simultaneous fit to the six outburst spectra plus the averaged quiescent spectrum. The bremsstrahlung temperature was fixed at 30 keV while the column of the partial absorber was common to all spectra, and gave a best fit value of $170\pm40\times10^{22}$ cm^{-2}. The covering fraction of the partial absorber, the column of the simple absorber, and the normalization of the bremsstrahlung were fitted to each spectrum individually, and the resulting values are shown in Fig. 6. For this figure, and when estimating the change in accretion rate (Section 5.3), we decreased the normalisation of the quiescent spectrum by half, to account for the fact that we are probably seeing both poles in quiescence but only one in outburst (see Section 5). Thus, even though there is ambiguity in the model fits, the values in Fig. 6 are likely to be a truer representation of the outburst than those in Fig. 2.

We have also investigated the spectral changes over the spin cycle in the outburst observations (in quiescence the pulse amplitude and count rate are too low for phase-resolved analysis). We found that the spin pulse is almost purely a simple change in the intensity, with no accompanying change in the spectrum. As an illustration Fig. 7 shows the data from the peak of outburst (observation 6) binned into a spin-maximum spectrum (when the count rate was >60 per cent of the mean) and a spin-minimum spectrum (count rate <40 per cent of the mean). The spectra were fitted with the same model of a 30 keV bremsstrahlung and an iron line, absorbed by a 30×10^{22} cm^{-2} simple absorber and a 170×10^{22} cm^{-2} absorber covering 0.60 of the source. Allowing only the normalization to change between the spec-

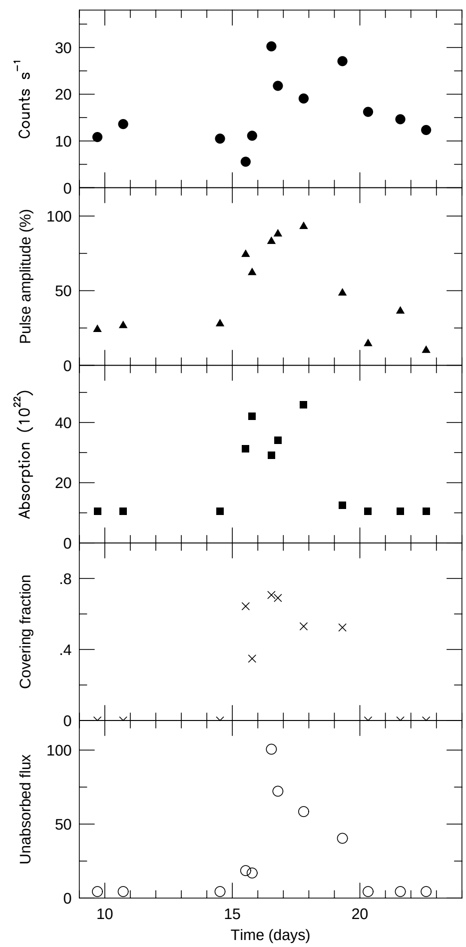

Figure 6. A version of Fig. 2 but using a more complex absorption model. The top two panels are the mean count rate and the pulse amplitude, as in Fig. 2. The lower three panels result from fitting the data with a 30 keV bremsstrahlung absorbed by both a simple absorber, whose column density is shown in the middle panel, and a dense 1.7×10^{24} cm^{-2} partial absorber, whose covering fraction is given in panel second from bottom. The bottom panel shows the normalisation of the bremsstrahlung in this model. The quiescent points all have the same value in the lower panels, since the model was fitted to their average. Again, the uncertainty in the values results from the flickering in such short observations, and from the ambiguity in the fitted models. Thus the photon noise error bars are in all cases small compared to the scatter in the points.

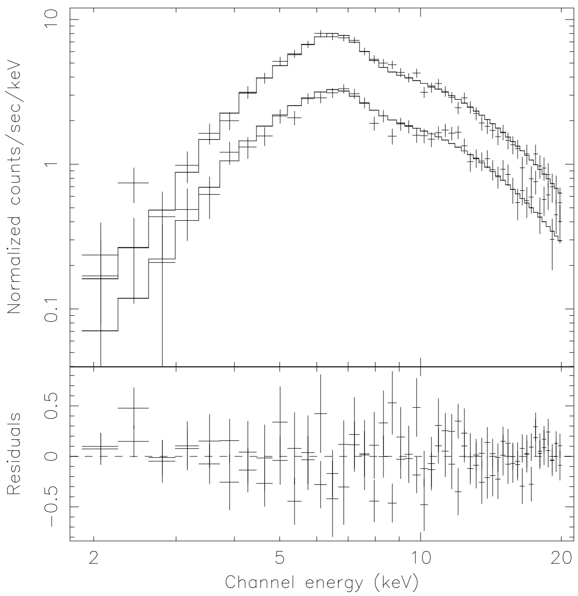

Figure 7. The pulse maximum spectrum from the peak of the outburst (observation 6) compared with the pulse minimum spectrum from the same observation. The fitted models are the same except for a change in normalization.

tra gives a χ^2_ν of 0.98. The hardness ratio from all outburst observations combined does show a slight change over the spin cycle, getting harder at spin maximum (Fig. 4), but the phase resolved spectra from individual observations are still adequately fit without including this effect.

5 INTERPRETATION

To present our interpretation we need to review the results of the eclipse study in Hellier (1997a). This concluded that accretion occurred onto two approximately equal poles at latitudes between 43° and 63°. Each pole crosses the white dwarf face in half a spin cycle, at which point its disappearance compensates for the simultaneous appearance of the other pole. Thus, with one of the accretion regions always visible, and with spin-phase varying absorption playing little role in this star, the spin pulse has a low amplitude and a complex shape, probably dependent on slight asymmetries between the poles. The eclipse study also shows that the upper pole appears at phase 0.25 and disappears at phase 0.75, on the phasing adopted in this paper and Hellier (1997a).

5.1 Hiding the lower pole

In outburst the pulse amplitude jumps to 90 per cent. Thus, either the outburst alters the balance between the poles such that one becomes 10 times brighter than the other, or one of the poles must be hidden. The former is unlikely, since an accretion disc is expected to feed both poles of a dipole roughly equally, regardless of whether or not it is in outburst. Any asymmetry would be due to the structure of the field, and so would also be present in quiescence. Hiding the lower pole, though, can occur owing to the peculiarly high inclination of XY Ari, as we now discuss.

If we assume that XY Ari accretes in equilibrium during quiescence, and thus that the disc is disrupted at the point where the Keplerian frequency of the disc equals the rotational frequency of the white dwarf (it cannot be much further out otherwise the centrifugal barrier would inhibit accretion), we have, for a 206-s spin period and a ~ 1 $M_\odot$ white dwarf, an inner disc extending inwards to 9 white dwarf radii ($R_{\rm wd}$). At the inclination of XY Ari ($80 < i < 84$; Hellier 1997a) the bottom of the white dwarf is only barely visible in quiescence (which, indeed, placed the upper limit of 84° on the inclination).

The increased mass accretion rate in outburst, however, will reduce the radius of disc disruption according to $r \sim \dot{M}^{-2/7}$ (e.g. Frank, King & Raine 1992). Since there are no substantial spectral changes in outburst, other than the increased absorption, we can take the unabsorbed bremsstrahlung flux as an indicator of the relative accretion rates. Depending on the absorption model the unabsorbed flux, and therefore $\dot{M}$, increases by a factor ~ 24 between quiescence and the peak of outburst (Fig. 6). This corresponds to a 60 per cent reduction in the inner disc radius, $R_{\rm mag}$, to ~ 4 $R_{\rm wd}$ (see Fig. 8).

At $R_{\rm mag} = 4$ $R_{\rm wd}$ the disc will obscure the white dwarf down to a latitude of –19° (for $i = 84°$) or –34° (for $i = 80°$). Hence, since the lower accretion region has a latitude between –43° and –63° (in quiescence) it will not be seen during the outburst. Although the accretion regions will probably change latitude in outburst, this calculation assumes zero disc thickness at the disruption point, and so in reality more of the white dwarf will be hidden.

As a result the spin pulse will be close to total, with pulse maximum occuring when the upper pole is on the visible face and a deep minimum occuring when it lies behind the white dwarf. This is indeed the phasing of the observed pulse, which has flux maximum at phase 0.5, quarter of a cycle after the upper pole appears at phase 0.25. Further the absence of spectral change over the pulse is exactly as expected for a pulsation caused essentially by occultation.

5.2 The spin pulse in outburst

The residual flux at spin minimum cannot result from lower-pole emission leaking through the disc, since this would be much more absorbed than the pulse maximum spectrum, and no change in absorption is seen. Thus the residual emission implies that the upper accretion region is sufficiently extended that some of it is always on the visible face, even when the bulk has passed over the limb.

Indeed, there are two further indications of this. First, if the upper accretion region lay, at some phases, entirely on the visible face or entirely on the hidden face, it would produce a flat-topped or flat-bottomed pulse. However the observed pulse near the peak of the outburst is sinusoidal. Hence, parts of the upper accretion region must be continually appearing and disappearing at all spin phases.

The emission site is expected to be an arc extending along a ring of approximately constant magnetic latitude around the magnetic pole, with a gradient in accretion rate along it so that maximum accretion occurs furthest from the spin axis. This is discussed further in Hellier (1997a), who showed that the offset angle of the magnetic axis from the spin axis is $8° < \delta < 27°$ and that the magnetic colatitude of the accretion regions, ϵ, is $\sim 19°$ in quiescence. In outburst,

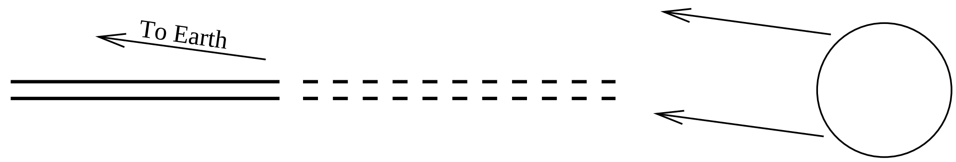

Figure 8. A scale drawing of XY Ari. The inner disc extends inwards to ~ 9 $\mathrm{R_{wd}}$ in quiescence and to ~ 4 $R_{\rm wd}$ in outburst. The lower accretion pole is visible in quiescence but not during outburst. The arrows are drawn for an inclination of 82°.

the decrease in $R_{\rm mag}$ increases the magnetic colatitude of the accretion, so that we expect $\epsilon \sim 30^\circ$ for accretion from 4 $R_{\rm wd}$. Part of the ring will always be in the visible hemisphere if $\epsilon > \delta - (90 - i)$, which is almost certainly satisfied in outburst.

In order to explain the sinusoidal pulse at the peak of outburst we then require an accretion arc extended sufficiently along the ring to ensure that some of the accretion is always in the visible hemisphere. There is no simple analytical expression for this requirement, but the arc length must exceed 180° unless $\delta < (90 - i)$. This means that the pole picks up at least some material from the disc at azimuths at which the majority of the material is flowing to the other pole. This is energetically possible if the disc is thickened out of the disc plane.

Notice, though, that during the outburst rise and also during the decline the pulse profile is flat-topped. Thus we suppose that the spread of accretion round the ring is not as extensive during the rise and the decline, and thus that the range of azimuths over which accreting material is picked up is a function of the accretion rate.

The second indication that part of the upper pole is always visible comes from the eclipse egress timings presented in Hellier (1997a). The egress times will depend on the location of the accretion region on the white dwarf, and thus on spin phase. The quiescent egresses can be divided into those of the upper pole (which occur earlier, since the angle of the secondary star limb causes the upper part of the white dwarf to emerge slightly earlier) and those of the lower pole (which occur later). At the peak of the outburst (observation 6) the egress occurs when the upper pole should be on the hidden face of the white dwarf, but it occurs too early to result from the emergence of the lower pole. Thus it again implies that, at least in outburst, part of the upper pole is always visible, even when the bulk is on the hidden face.

In the quiescent observations (Hellier 1997a) we used the eclipse egresses to estimate the size of the accretion regions, finding that they are <0.002 of the white dwarf surface. We cannot easily make a similar estimate in outburst because the three observations at the peak of outburst all emerge from eclipse near spin minimum, when the count rate is too low to make a reliable estimate of egress duration, and further, because one of the three suffers a data dropout just at egress. The preceding discussion implies that the accretion arcs are greatly extended in magnetic longitude compared to quiescence, but since we have no estimate of their width (extent in magnetic latitude) we can't estimate their fractional area, f. A complete ring with $\epsilon \sim 30^\circ$ would enclose an area of $f = 0.067$, and this number is important in determining the shape of the lightcurve, but the accretion will only occur around the perimeter of this area.

Having explained the spin pulse in outburst we can further explain the slight rise in hardness ratio at pulse maximum. Some of the X-rays from the shock will be reflected by the white dwarf and these will have a harder spectrum, since the softer photons are preferentially absorbed in the white dwarf atmosphere (e.g. Done, Osborne & Beardmore 1995). The reflected component will be seen preferentially when the accretion area is face on, that is at spin maximum, and so produce the increase in hardness ratio. The same effect is seen in AM Her stars when the accretion region faces us (Beardmore et al. 1995).

In addition to explaining the enhanced spin pulse during outburst the above picture also accounts for the increased absorption. There is substantial observational evidence that discs in DNe thicken during outburst, producing absorbing along lines-of-sight at angles up to $\sim 20^\circ$ above the plane (e.g. Mason et al. 1988). At the high inclination of XY Ari this ensures that the flux from the upper accretion region will encounter the extra absorption seen in the spectra.

5.3 The change in $\dot{M}$

To check the plausibility of the interpretation we can make order of magnitude estimates of the accretion flow, $\dot{M}$. At the peak of the outburst the accretion rate is 24 times that in quiescence (scaling it by the normalisations of the X-ray spectral fits, and assuming that only the upper pole is seen in outburst). The increased $\dot{M}$ through the inner disc means that the ram pressure ($\propto \dot{M}$) overwhelms the magnetic pressure at the original magnetosphere. Thus only a fraction of the increased material accretes immediately (the X-ray normalisations rise by a factor 4; Fig 6) and most of it pushes the disc inwards from ~ 9 $\mathrm{R_{wd}}$ to ~ 4 $\mathrm{R_{wd}}$ where the magnetic pressure ($\propto r^{-6}$) is sufficient to establish a new equilibrium. Here, the flow from the inner disc again matches the flow into it and the luminosity reaches 24 times the quiescent value.

The delay of 0.3–2 d (Fig. 1) is the time taken to fill the disc between ~ 9 and ~ 4 $\mathrm{R_{wd}}$. With a quiescent accretion rate of $3{\times}10^{16}$ $\mathrm{g\,s^{-1}}$ (Warner 1997) it implies a mass of $\sim 5{\times}10^{22}$ g for this section of disc. Using an outer disc radius of ~ 60 $\mathrm{R_{wd}}$ (Allan et al. 1996), and assuming a constant surface density, the total mass of the disc is $3{\times}10^{24}$ g. Further, again scaling from the X-ray luminosities, the total mass accreted over the 5 days of outburst is $1.5{\times}10^{23}$ g.

For comparison, the theoretical disc by Ichikawa & Osaki (1992), adjusted for the parameters of U Gem, has a to-

tal mass of 7×10^{23} g and deposits 8×10^{22} g onto the white dwarf each outburst. A model by Cannizzo, Wheeler & Polidan (1986) has a total mass of 2×10^{24} g and again deposits 8×10^{22} g per outburst. These values agree with our values to within the observational uncertainties.

5.4 The story of the outburst

We summarise the above as follows. In quiescence the disc is disrupted at $\sim 9\ R_{\rm wd}$, allowing a clear view of the white dwarf. Accretion occurs roughly equally onto both poles. The appearance/disappearance of one pole compensates for the disappearance/appearance of the opposite pole, producing a low-amplitude pulse as the white dwarf spins.

Day 1: A disc instability occurs somewhere in the disc, feeding material towards the magnetosphere at an increased rate. The magnetosphere shrinks and the inner disc occults the lower pole. Left alone, the upper pole now produces a large amplitude spin pulse as it cycles from the visible face to the hidden face. Some of the increased mass flow reaches the white dwarf and the intrinsic X-ray emission increases by a factor 4. However, since we are no longer seeing the lower pole, and since the upper pole suffers increased absorption, the observed count rate drops. The material accretes onto part of the ring around the white dwarf, and at some spin phases the accreting region is entirely on the visible face, producing a flat topped spin pulse.

Day 2: The mass flow onto the white dwarf increases dramatically, producing a 24-fold increase in X-ray emission over quiescence. Thus, even with the increased absorption, the observed average count rate becomes three times that in quiescence. Since the material is now connecting to field lines much further in ($\sim 4\ R_{\rm wd}$) the magnetic colatitude of the accretion region climbs from $\sim 19^\circ$ to $\sim 30^\circ$. Accretion also arrives from a greater range of azimuth, extending the accretion arc around the pole towards a complete ring. Parts of the extended ring are therefore always disappearing and appearing over the limb of the white dwarf and this, coupled with a gradient in accretion rate along the ring, produces a sinusoidal spin pulse.

Days 3 & 4: The accretion rate and the observed count rate decline gradually.

Day 5: The accretion rate drops further and the magnetosphere expands. The absorption decreases and so the observed count rate increases, despite the lower accretion rate. The lower pole begins to appear again and the pulse amplitude drops, with flux from the lower pole filling in the minima. The accretion ring at the upper pole shrinks and again lies entriely on the visible hemisphere at some spin phases; thus the spin pulse again becomes flat topped.

Day 6: XY Ari returns to quiescence.

5.5 Modelling the spin pulse

To back up the results so far we present some simple modelling of the accretion regions and thus of the spin pulse profiles. The model follows that by Kim & Beuermann (1995), tracing magnetic field lines back from the disc disruption radius, $R_{\rm mag}$, to their location on the white dwarf. The geometry is completely specified by $R_{\rm mag}$, δ and i, and by assuming a dipolar field and a negligible shock height.

As the accretion rate is likely to be greatest along 'downhill' fieldlines, we have introduced a function, $A \pm B\cos\alpha$, where α is the angle between the tangent to the field and the disc at the capture point. This weights the intensity of the X-ray emission around the rings, using opposite signs of B for the upper and lower pole respectively. Depending on the choice of A and B the emission can occur from all points on the ring ($A = 0$), a 180° arc ($B = 0$), or somewhere inbetween. The code sums the flux from the accretion regions not obscured by the white dwarf, ignoring absorption effects.

Fig. 9 shows simulations with the parameters adjusted to match the XY Ari pulse profiles (Fig. 3). The bottom curve uses parameters suitable for quiescence ($i = 82^\circ$, $\delta = 15^\circ$, $R_{\rm mag} = 9\,{\rm R_{wd}}$) and assumes that both poles are visible and are equally bright. If such a model is entirely symmetric no net modulation is seen. The low-amplitude modulation seen in quiescence requires symmetry breaking, for instance a non-zero shock height of order 0.01 $R_{\rm wd}$ or a dipole placed off center by $\sim 0.05\ R_{\rm wd}$. Thus for the bottom curve the dipole was offset by 0.05 $R_{\rm wd}$ in a direction perpendicular to the plane formed by the spin axis and the (centred) dipole axis. This reproduces the small peak at phase 0.7 (Fig. 3).

The top profile in Fig. 9 uses the reduced $R_{\rm mag}$ of 4 $R_{\rm wd}$ and assumes that only the upper pole is visible, as deduced for the peak of outburst. In order to obtain the ~ 90 per cent modulation depth the arc length has to be $\gtrsim 210^\circ$.

The middle profile uses $R_{\rm mag} = 7\ R_{\rm wd}$; this reduces ϵ compared to the outburst peak, and so the upper pole lies entirely on the visible face of the white dwarf at some spin phases, producing a flat-topped profile. We have assumed that the lower pole is partially visible, and given it a 50 per cent weighting compared to the upper pole. This fills in the mimima, producing a pulse profile comparable to that during the decline from outburst (the slight asymmetry in the curve arises because the off-centered dipole was used for all three curves).

Figs. 9 & 3 show that the model reproduces the gross features of the data. There are some discrepancies, for instance the flat-topped section of the pulse observed during the decline lasts longer than in the model. However, several inputs to the model, such as the choice of dipole asymmetry and the weighting of accretion rate with azimuth, are very uncertain.

6 A POSSIBLE ALTERNATIVE?

Despite the above there is an alternative interpretation which we can't rule out. As outlined in Section 2, at least some outbursts in IPs may be caused by secondary star instabilities. Further, Hellier et al. (1989) suggested that during an outburst of EX Hya the increased mass transfer stream overflowed the initial impact with the accretion disc and continued on a ballistic trajectory to an impact with the magnetosphere. This could cause material locked in orbital phase to feed onto field lines rotating with the spin cycle, and so produce an accretion geometry varying with the beat (spin–orbit) frequency. Thus, Hellier et al. (1989) predicted that EX Hya in outburst should show an X-ray beat pulse. Although no such observation has yet been made this idea

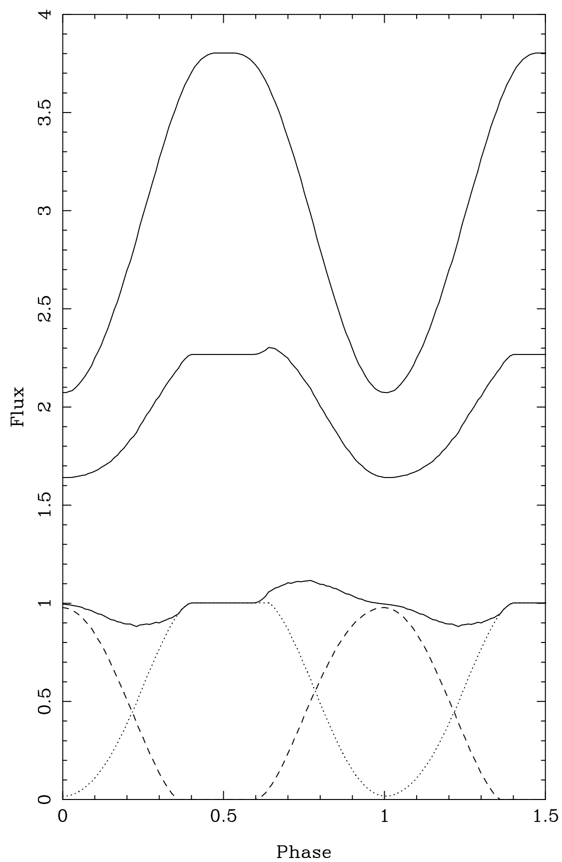

Figure 9. Model spin pulse profiles with parameters adjusted for outburst, decline from outburst, and quiescence (top to bottom respectively). See Fig. 3 for comparable data. The profiles are all normalized to 1, and the middle and upper profiles are offset by 1 and 2 units respectively. For the quiescent profile the contributions of the upper pole (dotted line) and lower pole (dashed line) are also shown.

seems to apply to other IPs in quiescence (Hellier 1993b; 1997b).

Unfortunately, since the current data on XY Ari are sampled over such a limited range of orbital phase (15 min near egress from a 6 h orbit), there is no way of telling whether the pulsation is at the spin period or the beat period. Thus the large changes in the pulsation from quiescence could be explained if a stream overflowing in outburst causes a beat period pulsation which is not present in quiesence.

We consider this less likely, though, for three reasons. First, XY Ari has both a wide orbit and a short spin period compared to other IPs, and therefore a small magnetosphere. A ballistic trajectory (see e.g. Lubow 1989) would have a closest approach to the white dwarf of $\sim 9{\times}10^9$ cm, outside the magnetosphere of $\sim 5{\times}10^9$ cm. Thus it would probably interact with the disc rather than the magnetic field (see Hellier 1997b for more discussion of this point amongst IPs). Secondly, the other aspects of the outburst, which fit into the disc-instability picture outlined above, do not find a ready explanation in this picture. Thirdly, the probable 'mass-transfer' outbursts in EX Hya, TV Col and V1223 Sgr have several differences from normal outbursts, including being very short at 1–2 d duration. The present outburst of XY Ari is longer at 5 d, which is more typical of normal DN events. Thus we do not adopt the disc-overflow idea in interpreting XY Ari, but an X-ray lightcurve round a full orbital cycle in outburst would distinguish the spin period from the beat period, and so settle the issue.

Even if the changes in the pulsation are caused by the inner disc pushing inwards, rather than by disc overflow, it is conceivable that the extra material could still originate from a mass transfer event, rather than a disc instability, but we can't distinguish between these possibilities with our current data.

7 DISCUSSION

Our *RXTE* observations of XY Ari over a 30-d period show an outburst lasting 5 d. The intrinsic X-ray luminosity at the peak of outburst was 24 times that in quiescence. On the dubious assumption that the optical flux increased by the same amount the optical amplitude would have been ~ 3 mag, typical of DNe. The recurrence time is much harder to estimate. This is the first outburst to been seen, while, in addition to our *RXTE* data, XY Ari has been observed with *Einstein*, *Ginga* and *ASCA* on 7 occasions and in the infra-red on at least 5 occasions, counting an 'occasion' as a period of ~ 5 d (for references see the introduction). Thus we can only conclude that the time spent in quiescence is $\gtrsim 10$ times the length of outburst.

During outburst the large, sinusoidal X-ray spin pulse is caused by an upper accretion pole disappearing and reappearing over the white dwarf limb as the white dwarf rotates. This behaviour is similar to the model of IP spin pulses proposed by King & Shaviv (1984). Although we envisage the accretion region to be a ring surrounding the upper magnetic pole, rather than the filled circle considered by King & Shaviv, the effect will be similar as far as the pulse profile is concerned. Hellier, Cropper & Mason (1991) criticized King & Shaviv's model on the grounds that it required that the lower pole be hidden, otherwise symmetry would produce no net modulation. Hellier et al. showed that neither the disc nor the accretion flow could hide the lower pole in a typical IP and concluded against the model as a general explanation of the spin pulsations in IPs, instead looking to absorption to create the pulses.

Several circumstances combine in XY Ari, though, to make the King & Shaviv (1984) model apply during outburst. The inclination ($>80^\circ$) is the highest amongst the known IPs; its unusually small spin period (206 s) implies a small magnetosphere; and the increased mass transfer in outburst further reduces the magnetosphere by half. The three effects combine to obscure the lower pole (see Fig. 8) in a manner which wouldn't occur in a system with a lower inclination or a larger magnetosphere. As a further indication of the different behaviour of XY Ari in outburst, its X-ray spin pulse is the only one to show increased hardness at flux maximum, whereas virtually all other systems show a softer (less absorbed) spectrum at maximum (e.g. Ishida 1991). See Hellier (1997a) for further discussion of the spin pulse in XY Ari and how it differs from that in other IPs.

GK Per is the only other IP to have been observed in outburst in X-rays, and the similarity with XY Ari is striking. GK Per again has a short spin period (351 s) and thus

a small magnetosphere. It also has a low-amplitude complex spin pulse in quiescence (e.g. Ishida et al. 1992), which could well imply an asymmetry between the poles. In outburst the pulse amplitude is much larger and the pulse profile simpler (Watson et al. 1985). Clearly the same mechanism of blocking the lower pole in outburst might apply to GK Per, which would require that it has at least a moderately high inclination.

7.1 Application to 'non-magnetic' systems

Following from the above we can try to apply the idea to non-magnetic CVs to explain dwarf novae oscillations (DNOs). These are quasi-periodic oscillations seen both in the optical and X-ray in many DN during outburst. Warner (1995b) reviews the observations and argues that they imply fields of 10^4–10^5 G, below those of IPs but sufficient to channel the accretion flow close to the white dwarf. The lower coherence of the oscillations results from the surface layers of the white dwarf slipping under the influence of accretion, whereas the higher field in IPs binds the surface to the core.

While explaining much of the DNO phenomenology this doesn't explain why the oscillations are seen preferentially in outburst. In fact, since the magnetospheres will be larger in quiescence, one might expect better channelling and larger pulsations in quiescence. If again, though, both poles are seen in quiescence, but the disc pushes inwards to obscure the lower pole in outburst, the broken symmetry will lead to larger pulsations in outburst.

Systems with B $\sim 10^4$–10^5 G will have smaller magnetospheres than XY Ari, but, in general, the inclinations will also be smaller, allowing the same transition between viewing two poles and viewing one pole when the accretion rate changes.

Such fields have additionally been proposed as an explanation for the UV delay seen in some DNe, where the UV flux rises ~ 12 h after the optical flux (e.g. Hassall et al. 1983). Such a field would empty the inner (UV emitting) part of the disc in quiescence. Livio & Pringle (1992) propose that at the start of an outburst the disc material has to refill the depleted region before accreting, explaining the delay in the rise of the higher energy flux. The fact that we see exactly that in XY Ari supports this idea. In our data the increased absorption and blocking of the lower pole, indicating changes in the disc, are seen the day before the major rise in X-ray flux. During this time the inner disc is diffusing inwards and collapsing the magnetosphere (Section 5.3).

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